Arctic Ocean Simulation, 1948–2002

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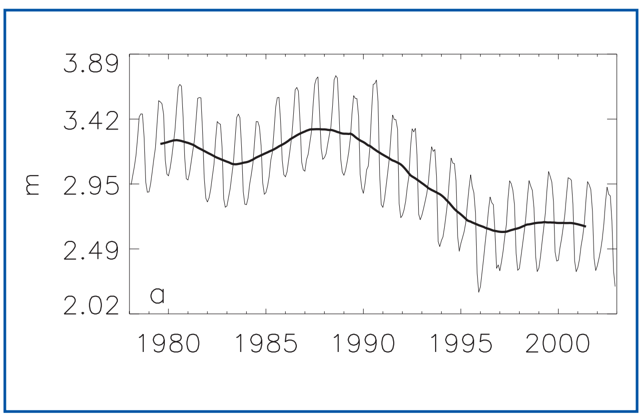
Recent measurements indicate that the sea ice cover in the Arctic has thinned significantly over the past 20 years. Some studies suggest that the observed thinning appears to be associated with natural variability in atmospheric circulation patterns at high latitudes, which drive ice transport in and out of the Arctic. Other studies indicate that sea ice thinning was induced by warmer air temperatures, possibly due to enhanced, anthropogenic warming over the past two decades. The Arctic is expected to be the first place to feel the impact of climate changes, and a shrinking sea ice cover threatens the lives and livelihoods of animals and people who live in the region. A new ice-ocean coupled model developed at Los Alamos National Laboratory is used to investigate factors associated with the reduction of Arctic sea ice volume.

Model Configuration: The Los Alamos Parallel Ocean Program (POP) solves equations for the evolution of temperature, salinity, and currents. The Los Alamos Sea Ice Model (CICE) describes ice volume, area, and motion, featuring horizontal advection via a new incremental remapping scheme [1]. The ice and ocean models are fully coupled, with state information passing between them once every simulated day. They are forced by high-frequency atmospheric data and are discretized for nonuniform, general curvilinear grids. For the experiment described here, we use a 900×600 global mesh (approximately 0.4° resolution) with 40 vertical ocean levels, whose north pole is moved smoothly into North America to allow for more accurate representation of the Arctic. This simulation required approximately 36,000 CPU-hours on the Cray X1 at Oak Ridge National Laboratory.

Ice Area and Volume: We see no significant trend in ice area coverage or volume over the full 55-year simulation, but the model does produce an extended period of ice volume reduction in the late 1980s through the 1990s, shown in Fig. 1a, which has been observed [2]. Model results compare well with submarine-based upward looking sonar (ULS) ice drafts [3], although the model drafts tend to be slightly larger than the ULS data (Fig. 1b). ULS measurements were taken in the central Arctic, where our simulation also shows significant thinning (Fig. 2).

Any change in ice volume within the Arctic Ocean results from either thermodynamic processes (melting or freezing) or transport (import or export) between the Arctic and the world oceans. Transport tends to decrease the ice volume, while thermodynamic processes increase it, on average. For convenience, we compare quantities integrated (or averaged) over the two halves of the 25-year time period, 1978–1990 and 1990–2002. The total thermodynamic contribution to the volume decreases by 14,000 km^3 from the earlier period to the latter; increased melting at the base of the ice appears to be responsible. At



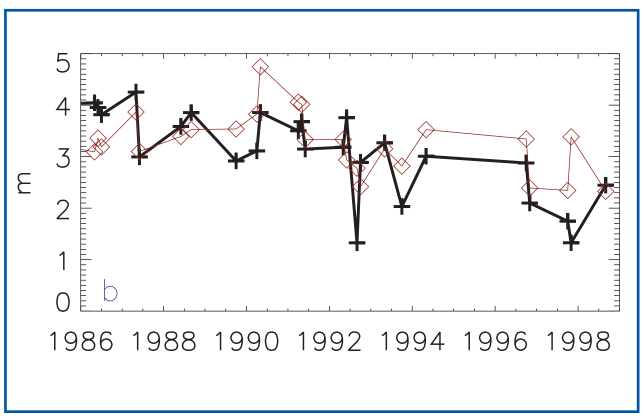


Figure 1— ***(a) Sea ice thickness, averaged over the Arctic. Heavy solid line is the 3-year running mean. (b) Comparison of sea ice model draft (◊) with submarine-based sonar data(+). We compute ice draft (depth below sea level) from ice volume and area, allowing for depression of the ice column by the snow load on top of it.***

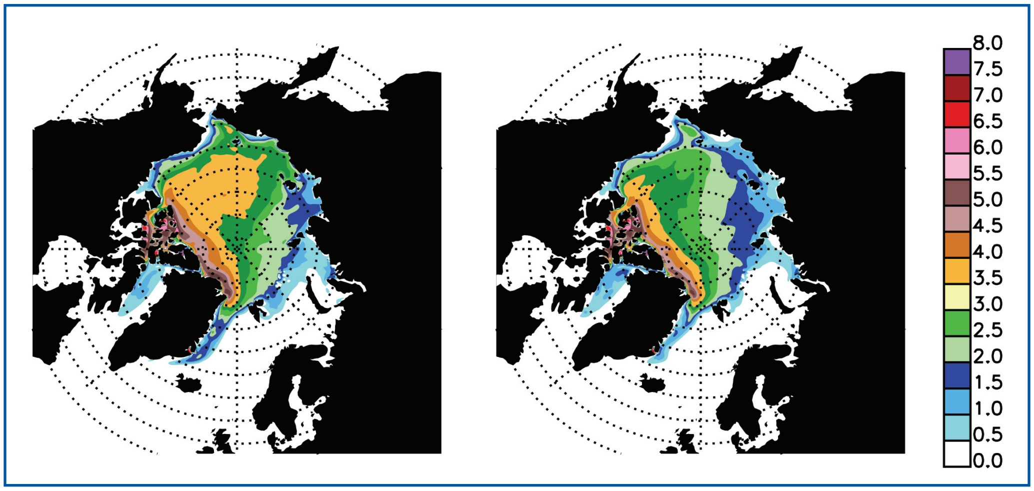


Figure 2—
August thickness averaged over (left) 1978–90 and (right) 1990–2002, in m.

the same time, ice export from the Arctic also decreases, most likely as a result of thermodynamically reduced ice volume within the Arctic basin, but by only 3,000 km^3. Thermodynamic production fails to keep pace with ice export, leading to a net reduction of the ice volume in the Arctic. Variations in sea ice extent and area coverage regulate the flux of heat from the Arctic ocean to the atmosphere; in this simulation, the average ice area decreased about 5%, allowing the ocean to warm more in summer and cool more in winter. However, atmosphere-ocean heat fluxes account for only a portion of the heat flux affecting the top 10 m of the ocean, where the ice is located.

The Heat Source: The Arctic Ocean warmed by an average of 0.34°C in the simulation, and heat fluxes from the ocean to the atmosphere and to the ice both increased from 1978–1990 to 1990–2002. The surplus heat arrived in the Arctic with lateral ocean mass transport from the south—total heat transport over 1978–2002 exceeded surface cooling by 23 terawatts. Advance of warm water into the western Arctic after 1978 agrees favorably with observed changes. For instance, the greatest increase occurs in the warm "Atlantic layer," from about 100 to about 1500 m deep in this simulation.

The essential piece in the puzzle is the connection between the upper ocean, where the ice is located, with greater ocean depths, where the heat is. Ocean mixing, which includes vertical convection to depths 100 m and more, intensified in the Arctic, possibly driven by more vigorous surface fluxes as the ice cover shrank. The balance of heat in the Arctic is delicate; this study suggests a key role for enhanced bottom melting associated with increased ocean heat transport to the Arctic.

[1] W.H. Lipscomb and E.C. Hunke, "Modeling Sea Ice Transport Using Incremental Remapping," *Mon. Wea. Rev.* **132**, 1341–1354 (2004).
[2] D.A. Rothrock, Y. Yu, and G.A. Maykut, "Thinning of the Arctic Sea-Ice Cover," *Geophys. Res. Lett.* **26**, 3469–3472 (1999).
[3] National Snow and Ice Data Center. Submarine Upward Looking Sonar Ice Draft Profile Data and Statistics. National Snow and Ice Data Center/World Data Center for Glaciology, University of Colorado at Boulder, 1998. Digital media.

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